

Production and decay of a heavy radion in Randall-Sundrum model at the LHC

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Abstract. We study production and decay of a radion predicted in the Randall-Sundrum model at the LHC. The radion is a scalar particle and its production and decay channels are quite similar to those of the Higgs boson. We find constraints on the model parameter space taking account of the results of the Higgs boson search at the LHC. We also study a possibility discriminating the radion from the scalar particles in the other model such as the supersymmetric standard model at the LHC experiments.

1 Introduction

A warped extra dimension model proposed by Randall and Sundrum (RS) [1] is one of the promising candidates of physics beyond the Standard Model (SM) to solve the gauge hierarchy problem. The RS model is formulated in the five-dimensional anti de-Sitter (AdS₅) space-time, and the extra (fifth) dimension is compactified on an orbifold S_1/Z_2 of a radius r_c . In the RS model, there are two 3-branes located at two orbifold fixed points on the coordinate of the fifth dimension $y = 0$ and $y = \pi r_c$. The former is called a hidden brane while the latter is called a visible brane. All the SM particles are confined in the visible brane and only the gravity is allowed to propagate into the fifth dimension. With this set-up, the hierarchy between the electroweak scale and the Planck scale is understood reasonably if the distance between two 3-branes (i.e., compactification radius r_c) and the AdS curvature (k) satisfies a condition, $kr_c = 10 \sim 12$. It is, therefore, necessary to stabilize the radius of the extra dimension to solve the gauge hierarchy problem. A simple stabilization mechanism of the distance between two branes is known as the Goldberger-Wise mechanism [2].

A radion is a scalar field which corresponds to the fluctuation of the distance between two 3-branes. After the stabilization of the compactification scale, the radion has a finite mass and couples to the trace of the energy-momentum tensor of the SM. As a result, production and decay channels of radion at the hadron collider are the same with those of Higgs boson in the SM.

In this presentation, we show results of our study about production and decay of the radion at the LHC. We find constraints on the mass and coupling of the radion from the results of the Higgs boson search at the LHC. We also examine a possibility to discriminate the radion from heavier Higgs bosons in the minimal supersymmetric standard model (MSSM). We found that, if the mass spectrum of

Higgs bosons in the MSSM follows so called the “decoupling scenario”, the decay channels into the weak gauge boson pair (WW and ZZ) are useful channels to distinguish the radion in the RS model from the heavier Higgs bosons in the MSSM at the LHC.

2 Production and decay of the radion

The radion couples to the trace of the energy-momentum tensor of the SM. The interactions of radion with SM fields are described by the following Lagrangian:

$$\mathcal{L}_{\text{int}} = \frac{\phi}{\Lambda_\phi} \{T_\mu^\mu(\text{SM}) + T_\mu^\mu(\text{SM})^{\text{anom}}\}, \quad (1)$$

where ϕ is the radion field and Λ_ϕ is its vacuum expectation value (VEV). The trace of energy-momentum tensor $T_\mu^\mu(\text{SM})$ is given by

$$T_\mu^\mu(\text{SM}) = \sum_f m_f \bar{f}f - 2m_W^2 W_\mu^+ W^{-\mu} - m_Z^2 Z_\mu Z^\mu + (2m_h^2 h^2 - \partial_\mu h \partial^\mu h) + \dots \quad (2)$$

while $T_\mu^\mu(\text{SM})^{\text{anom}}$ comes from the scale anomaly

$$T_\mu^\mu(\text{SM})^{\text{anom}} = \sum_a \frac{\beta_a(g_a)}{2g_a} F_{\mu\nu}^a F^{a\mu\nu}, \quad (3)$$

where a , β_a and $F_{\mu\nu}^a$ are the gauge index, the β -function and the field strength for a corresponding gauge group, respectively (for detail, see [3, 4]).

From eqs. (1), (2) and (3), we can calculate the decay rate of the radion into the SM fermions, gauge bosons and the Higgs boson. In Figure 1, we show the branching ratios of the radion decaying to the various SM particles as a function of the radion mass m_ϕ . The Higgs boson mass m_h in the final state is fixed at 125 GeV. Note that the dominant decay modes of radion are the WW , ZZ and hh channels for $m_\phi \geq 500$ GeV.

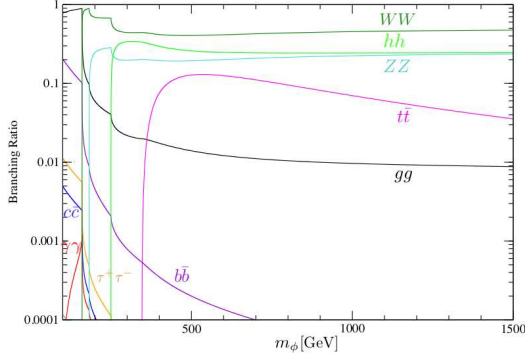


Figure 1. Branching ratio of the radion decaying to the SM particles as a function of the radion mass m_ϕ . For a decay to the Higgs boson pair, $\phi \rightarrow hh$, the Higgs boson mass is fixed at 125 GeV.

3 Constraints on the radion mass

The RS model is characterized by two parameters, m_ϕ and Λ_ϕ . Constraints on the parameter Λ_ϕ has been studied indirectly using the result of the 1st Kaluza-Klein graviton search at the LHC [5]. As mentioned in a previous section, the decay modes of the radion are completely same with those of the SM Higgs boson up to the couplings. In this section, therefore, we study constraints on m_ϕ and Λ_ϕ using the experimental data of the Higgs boson search at the LHC.

At the LHC, a signal of Higgs-like particle has been found at about 125 GeV in both ATLAS and CMS, and the wide mass region except for ~ 125 GeV has been excluded. For example, the ATLAS experiment excludes the mass smaller than 558 GeV from the decay channels $h \rightarrow WW$ and $h \rightarrow ZZ$ [6]. This mass bound may be understood as a lower mass bound on a scalar particle in some new physics models if the scalar particle couples to WW and ZZ . Since the radion also decays into both WW and ZZ , we examine constraints on the mass of the radion m_ϕ and the coupling Λ_ϕ from the results of ATLAS experiment. In the following, we study the allowed parameter space of the radion under the condition

$$\sigma(pp \rightarrow h) \times \text{Br}(h \rightarrow WW/ZZ) \Big|_{m_h=125 \text{ GeV}} \geq \sigma(pp \rightarrow \phi) \times \text{Br}(\phi \rightarrow WW/ZZ). \quad (4)$$

We show constraints on m_ϕ and Λ_ϕ taking account of the condition (4) in Figure 2. Two contours correspond to the 95% CL bounds obtained from the Higgs search limit in the WW channel (red) and the ZZ channel (blue), respectively. The inner of contours are excluded region. It can be seen from the figure that the radion mass m_ϕ should be larger than 500 GeV for $\Lambda_\phi < 5$ TeV. As Λ_ϕ increases, bound on m_ϕ is weakened. Note that constraints from $h \rightarrow ZZ$ are much stronger than those from $h \rightarrow WW$. For example, $m_\phi = 300$ GeV and $\Lambda_\phi = 8$ TeV is strongly disfavored by the experimental bounds for $h \rightarrow ZZ$ (not by $h \rightarrow WW$) at the LHC. However, the sensitivity of the WW mode for small m_ϕ is slightly better than ZZ mode.

From this result, we conclude that the radion lighter than ~ 300 GeV is disfavored from the Higgs search experiment at the LHC unless the parameter Λ_ϕ is larger than 10 TeV. Since too large Λ_ϕ is unfavorable because it may lead to a new hierarchy between the weak scale and Λ_ϕ , we focus on the heavy radion search at the LHC.

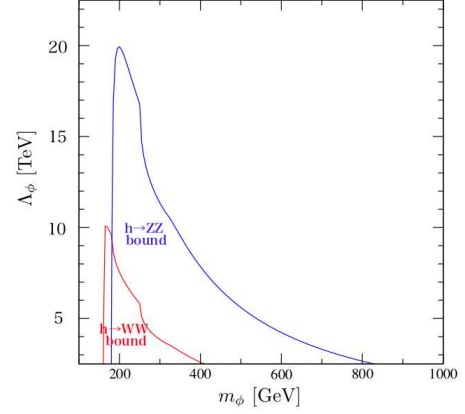


Figure 2. Constraints on m_ϕ and Λ_ϕ from the results of the Higgs search experiment at the LHC. The red and blue contours are obtained from the experimental bounds on the decay channels $h \rightarrow WW$ and $h \rightarrow ZZ$, respectively.

4 Radion vs. MSSM Higgs

Once a new scalar particle beyond the SM is found in the future LHC experiments, we must study if it is the radion or not, because various models predict an existence of neutral scalar particles. In this section, we examine a possibility to discriminate the radion from the heavier Higgs bosons in the MSSM as an example. In the MSSM, there are five Higgs bosons – two CP -even scalars (h, H), one CP -odd scalar (A) and two charged scalars (H^\pm). It is known that the mass of scalar particles discovered at the LHC, ~ 125 GeV, is very close to the upper limit of the lightest Higgs boson h in the MSSM. A possible explanation on the mass of h is known as so called “decoupling scenario” where the lightest Higgs boson h has almost same property with the SM while the other four Higgs bosons are much heavier than h and degenerate in mass. In the following, we identify the lightest Higgs boson h as a particle discovered at the LHC and compare the production and decay of the heavy neutral Higgs bosons (H, A) with those of the radion.

Figure 3 shows the production cross sections of the radion ϕ and MSSM Higgs bosons H, A at the LHC as functions of their mass. The dashed lines represent the radion with various values of the parameter Λ_ϕ from 2.5 TeV to 15 TeV. The solid lines in red and in cyan correspond to H and A , respectively. The cross sections of H and A are obtained for $\tan\beta = 30$ as an example, where $\tan\beta$ is a ratio of VEV of two Higgs doublets. It is easy to see that, when the mass is larger than 500 GeV, the production cross section of the radion is much larger than those of H and A for $\Lambda_\phi \leq 5$ TeV.

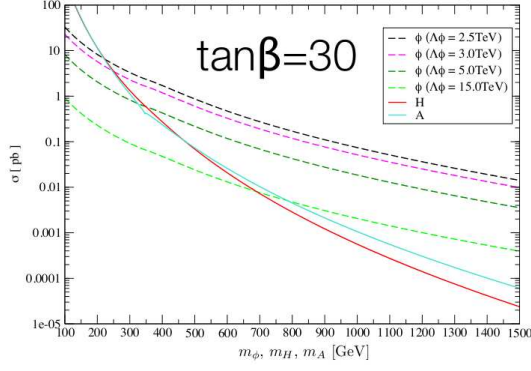


Figure 3. Production cross sections of ϕ, H, A as functions of their mass.

A distinctive feature of the decoupling scenario can be found in the interactions of the Higgs bosons. The interactions of the heavier Higgs bosons H, A to the weak gauge bosons W, Z are proportional to $\cos(\alpha - \beta)$, where α is the mixing angle of the mass matrix of the CP -even Higgs bosons. The decoupling scenario is realized when $\beta \simeq \alpha + \pi/2$ so that the interactions of H and A to WW and ZZ are highly suppressed. On the other hand, the interactions of radion to WW and ZZ have no suppression like H and A . We, therefore, expect relatively larger decay rates of the radion to WW and ZZ as compared to those of H and A , and these decay modes could be promising channels to distinguish the radion from the MSSM Higgs bosons.

We calculated the number of events N of the processes $pp \rightarrow \phi \rightarrow WW/ZZ$ at the LHC with the center-of-mass energy $\sqrt{s} = 7$ TeV and the integrated luminosity $\int dt \mathcal{L} = 15 \text{ fb}^{-1}$. The results are shown in Table 1 for $\Lambda_\phi = 8$ TeV and 15 TeV. In the table, the number of events of the $\phi \rightarrow ZZ$ mode is absent for $m_\phi = 200$ GeV. This is because that the radion mass $m_\phi = 200$ GeV is disfavored from the search of Higgs boson in the $h \rightarrow ZZ$ channel at the LHC as shown in Figure 2. We obtain the number of events more than a thousand (a few hundred) for $m_\phi = 200$ GeV and $\Lambda_\phi = 8$ TeV (15 TeV). Even for larger mass, $m_\phi = 500$ GeV, we obtain $O(10)$ events for both $\Lambda_\phi = 8$ TeV and 15 TeV in both the WW and ZZ channels. Note that, as already discussed, the decays into WW and ZZ of heavier Higgs bosons (H and A) in the decoupling scenario of MSSM are strongly suppressed. Thus, when a heavy and neutral scalar particle is discovered in the future

m_ϕ	200 GeV	500 GeV	1 TeV
$\Lambda_\phi = 8 \text{ TeV}$			
$\sigma \times \text{Br}(\phi \rightarrow WW)$	1.9×10^3	6.6×10	3.2
$\sigma \times \text{Br}(\phi \rightarrow ZZ)$	—	3.2×10	1.6
$\Lambda_\phi = 15 \text{ TeV}$			
$\sigma \times \text{Br}(\phi \rightarrow WW)$	5.4×10^2	1.9×10	9.0×10^{-1}
$\sigma \times \text{Br}(\phi \rightarrow ZZ)$	—	9.0	4.6×10^{-1}

Table 1. Number of events of the radion decay $\phi \rightarrow WW/ZZ$ at $\sqrt{s} = 7$ TeV for the integrated luminosity 15 fb^{-1} .

LHC experiment, we can expect to test a possibility of the radion using the WW and ZZ channels.

5 Summary

We have shown the results of our recent study for the production and decay of the radion in the RS model at the LHC. We first found constraints on the radion mass m_ϕ and the coupling Λ_ϕ from the experimental results of search for the Higgs boson at the LHC, since the radion has same decay channels with the Higgs boson. We examined a possibility to distinguish the radion from the other scalar particles such as the heavier Higgs bosons in the MSSM. The discovery of the Higgs-like particle at the LHC tells us that the decoupling scenario on the Higgs boson masses in the MSSM is one of the possible scenarios of the MSSM. We discussed that the decays into WW and ZZ are promising channels to discriminate the radion from the heavier Higgs bosons H, A in the decoupling scenario of the MSSM. When the radion mass is 500 GeV, a few $\times 10$ events are expected in the radion decays to WW and ZZ while decays of H and A into those final states are highly suppressed in the decoupling scenario of the MSSM.

The work of G.C.C is supported in part by Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology (No.24104502) and from the Japan Society for the Promotion of Science (No.21244036).

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